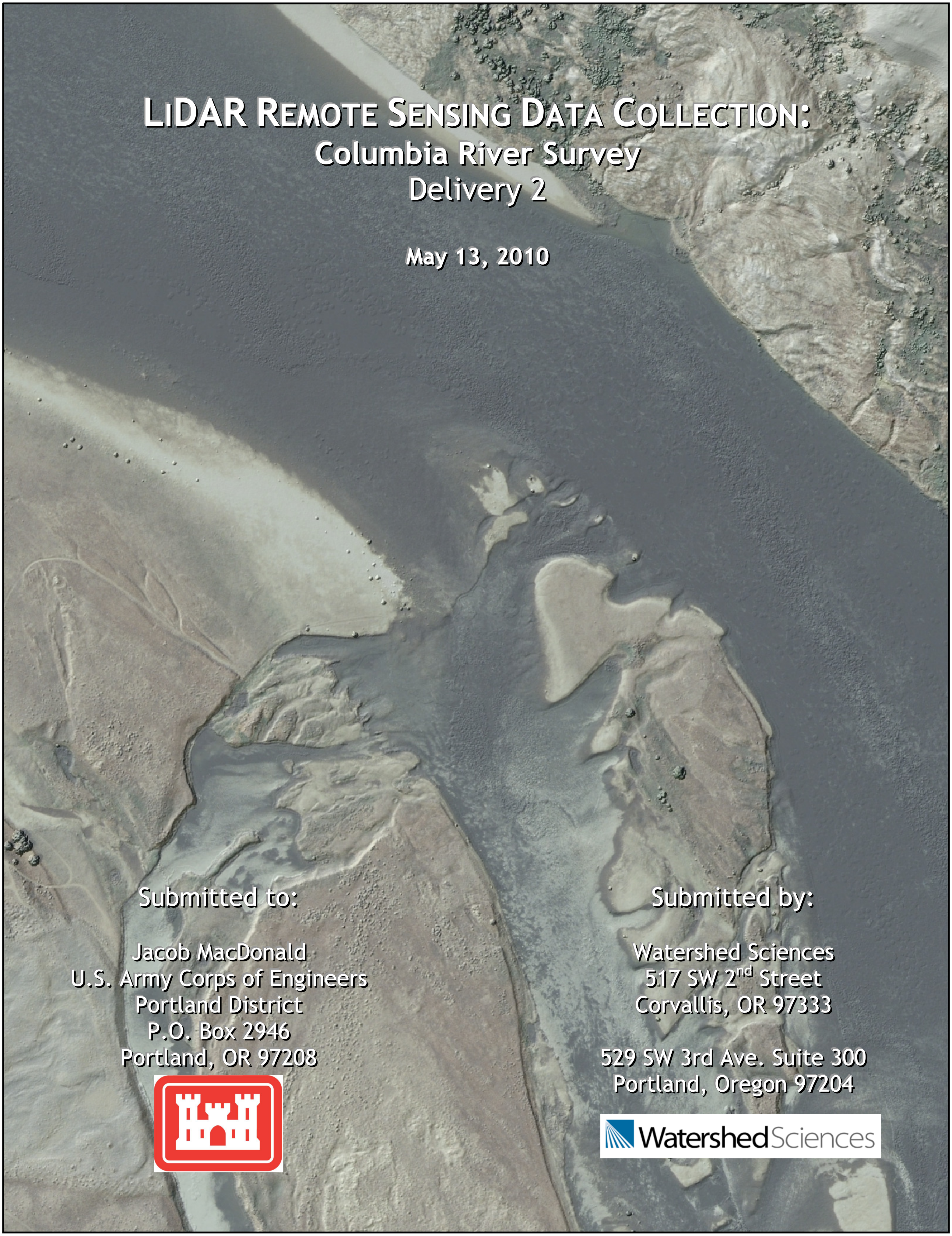

LiDAR Remote Sensing Data Collection:

Columbia River Survey

Delivery 2

May 13, 2010

Submitted to:

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Watershed Sciences

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TABLE OF CONTENTS

1. Overview

Watershed Sciences, Inc. (WS) is currently collecting Light Detection and Ranging (LiDAR) data of the Columbia River in Oregon, Washington, Idaho, and Montana. The requested AOI area for this delivery was 181,694 acres. The area was expanded to include a 100 m buffer to ensure complete coverage and adequate point densities around survey area boundaries, resulting in 191,071 acres of delivered data. LiDAR data for delivery two was collected between December 2nd, 2009 and February 5th, 2010 (**Figure 1**). This area includes portions of the Columbia River from Castle Rock to Woodland and extends southeast from Portland to the Bonneville Dam. This report contains maps and information specific to delivery 2, but has been appended to the previous delivered reports to generate a cumulative data summary for UTM Zone 10 and 11. Accuracy and density data will continue to be updated as additional data is processed.

***Figure 1**. Columbia River survey delivery status overview.*

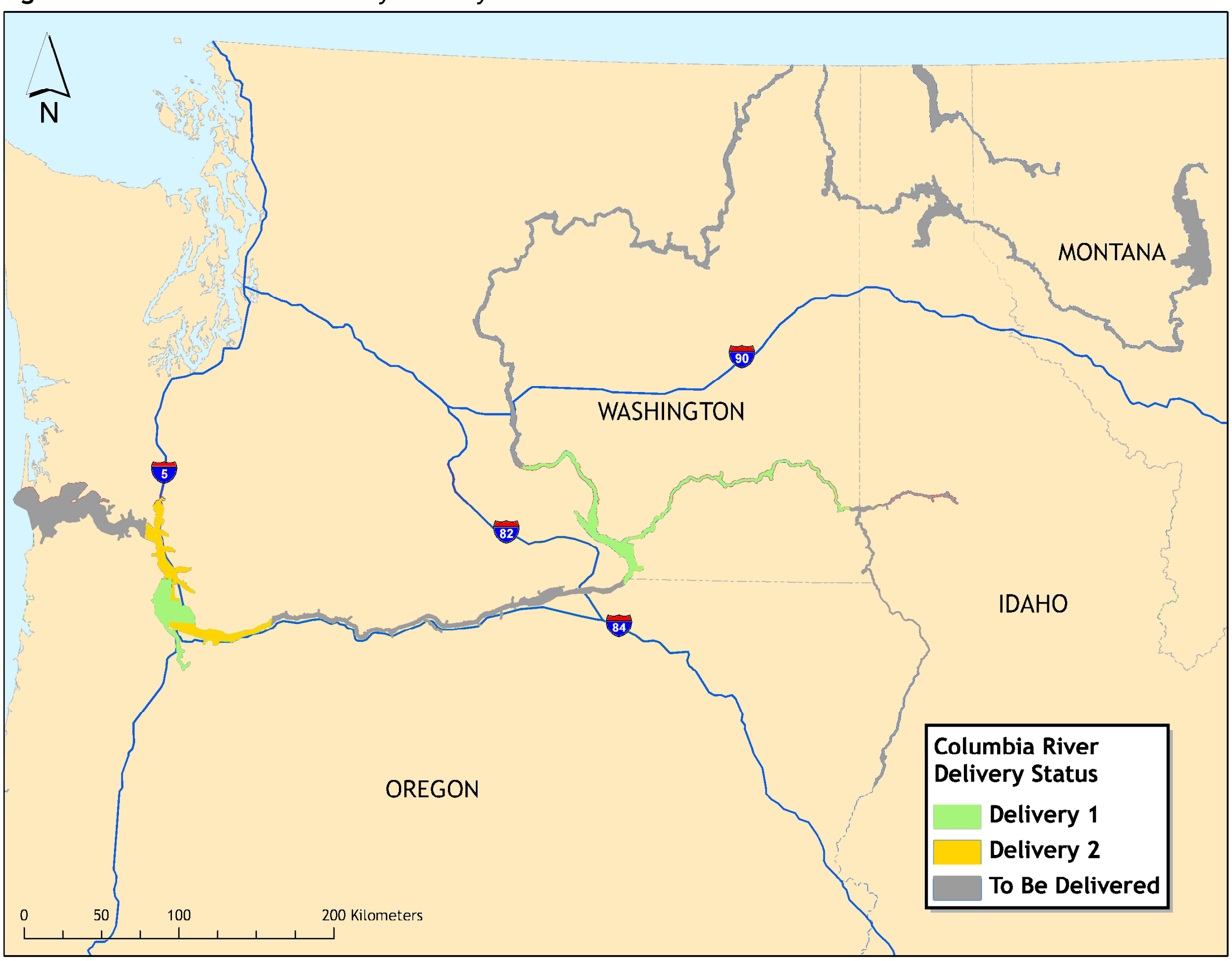


Table 1. *Columbia River, UTM Zone 10 and 11 LiDAR deliveries to date.*

UTM 10 Delivery	Date	Total Acres Flown	AOI Acres
1	April 15, 2010	129,000	125,409
2	May 13, 2010	191,071	181,694
UTM 11 Delivery	**Date**	**Total Acres Flown**	**AOI Acres**
1	April 15, 2010	206,500	187,764

2. Acquisition

2.1 Airborne Survey – Instrumentation and Methods

The LiDAR survey uses Leica ALS50 Phase II and ALS60 laser systems. For the Columbia River survey sites, the sensor scan angle was $\pm 14^{o}$ from nadir[1] with a pulse rate designed to yield an average native density (number of pulses emitted by the laser system) of $\geq$ 8 points per square meter over terrestrial surfaces. It is not uncommon for some types of surfaces (e.g. dense vegetation or water) to return fewer pulses than the laser originally emitted. These discrepancies between 'native' and 'delivered' density will vary depending on terrain, land cover and the prevalence of water bodies.

The Cessna Caravan is a stable platform, ideal for flying slow and low for high density projects. The Leica ALS60 sensor head installed in the Caravan is shown on the left.

All areas were surveyed with an opposing flight line side-lap of ≥60% (≥100% overlap) to reduce laser shadowing and increase surface laser painting. The Leica laser systems allow up to four range measurements (returns) per pulse, and all discernable laser returns were processed for the output dataset.

[1] Nadir refers to the perpendicular vector to the ground directly below the aircraft. Nadir is commonly used to measure the angle from the vector and is referred to a "degrees from nadir".

To accurately solve for laser point position (geographic coordinates x, y, z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the LiDAR data collection mission. Aircraft position was measured twice per second (2 Hz) by an onboard differential GPS unit. Aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft/sensor position and attitude data are indexed by GPS time.

2.2 Ground Survey – Instrumentation and Methods

The following ground survey data were collected to enable the geo-spatial correction of the aircraft positional coordinate data collected throughout the flight, and to allow for quality assurance checks on final LiDAR data products.

Trimble GPS survey equipment

2.2.1 Survey Control

Simultaneous with the airborne data collection mission, we conducted multiple static (1 Hz recording frequency) ground surveys over monuments with known coordinates (**Table 2)**. Survey control monuments were occupied by a Trimble GPS base station for an initial period of at least eight hours. All monuments were occupied during a subsequent second session with an observation period of at least four hours. Additional occupations were conducted as necessary. GPS measurements were made with dual frequency L1-L2 receivers with carrier-phase correction.

Watershed Sciences established monuments using aluminum survey caps provided by the Army Core of Engineers. Monuments were placed using 5/8" by 30" rebar covered with a 2" top aluminum cap stamped "U.S. Army C. of E. Portland Dist.". In addition, monuments were stamped in the field with the year and monument ID number.

As an initial check, the NGS on-line positioning user service (OPUS), was used to generate a corrected position for all base station observations. OPUS provides a measurement solution based on three surrounding continuously operating reference stations (CORS). OPUS output includes a solution report with positional accuracy confidence intervals for adjusted coordinates and elevations. The solution report is one component in assessing the quality of the OPUS GPS measurement solutions. Statistical checks of GPS base station positions and repeat control observations include the OPUS solution extended output report. In addition, the standard deviation, kurtosis, and skew of the measurement distribution for each base station occupation were compared. Longitude, latitude, and elevation distributions were separated, and graphic distributions of the positions were plotted for consistency.

Indexed by time, these GPS data are used to correct the continuous onboard measurements of aircraft position recorded throughout the mission. Control monuments were located within 13 nautical miles of the survey area(s).

David Evans and Associates (DEA) provided the official quality assurance and control checks of all monuments in the Columbia River project. DEA provided official coordinates for each monument through the OPUS online datasheet publication tool located on the USGS website. All monuments established by Watershed Sciences were published and made publicly available by DEA on the OPUS online datasheet website.

Table 2. *DEA Certified Survey Control coordinates for Delivery 2, UTM 10.*

Base Station ID	Datum: NAD83 (CORS91)		GRS80
	Latitude	Longitude	Ellipsoid Z (m)
1001-49	46.16527858	-123.1462071	-15.171
1001-51	45.54804226	-122.4121164	-13.122
1001-55	45.89961941	-122.7976048	-13.396
1001-56	45.85439383	-122.7026294	52.603
1001-57	46.04067492	-122.8670506	-14.22
1001-58	46.10915256	-122.8838243	-13.834
1001-69	45.60257664	-122.0437716	0.214
1001-70	45.91385943	-122.8034804	-13.482
86-19-305	46.19792934	-122.9130037	-6.618

2.2.2 RTK Survey

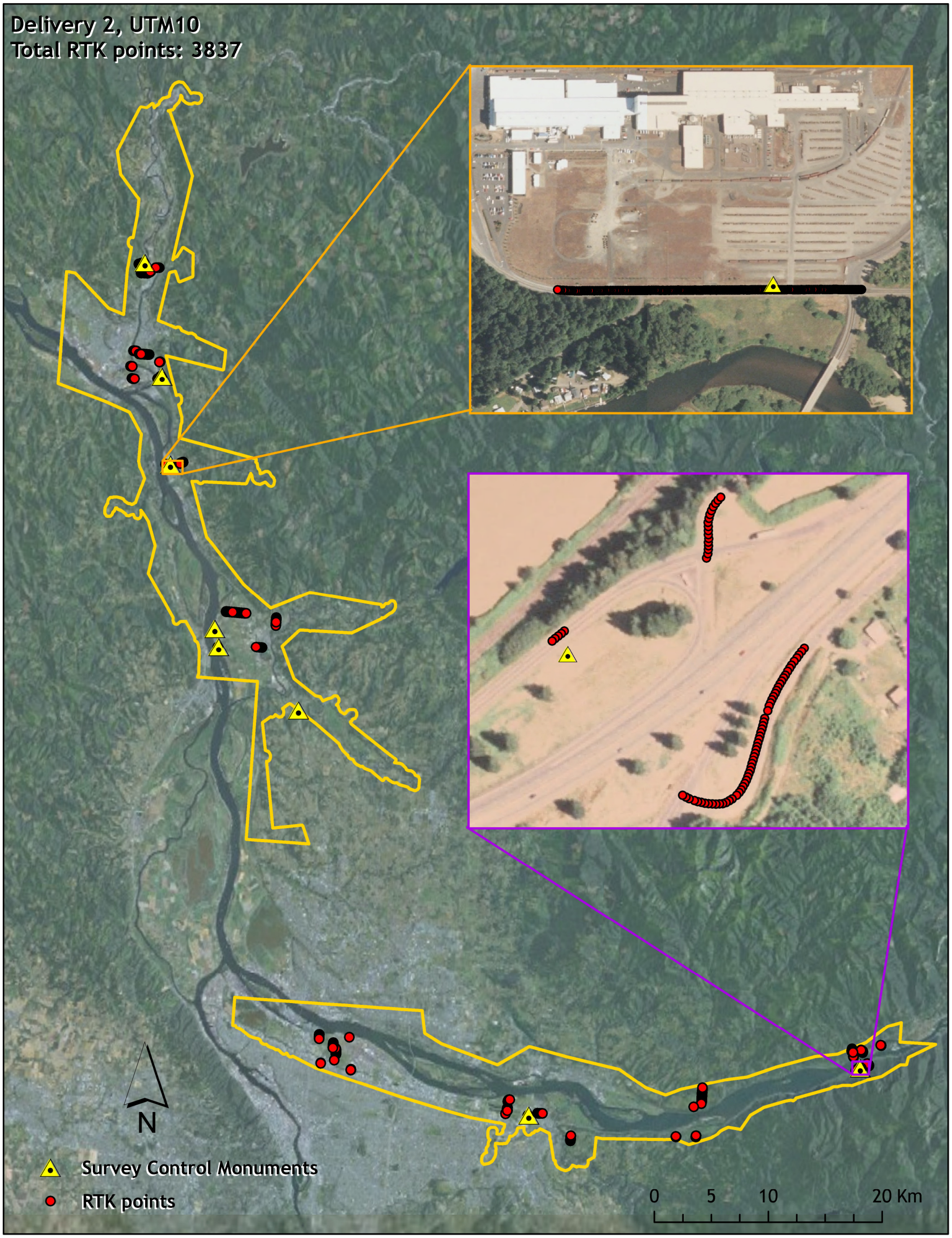
To enable assessment of LiDAR data accuracy, ground check points were collected using GPS based real-time kinematic (RTK) surveying. Instrumentation included multiple Trimble DGPS units (R8). RTK surveying allows for precise location measurements with an error (σ) of ≤ 1.5 cm (0.6 in).

For the RTK survey, the ground crew used a roving unit to receive radio-relayed corrected positional coordinates for all ground truth points from a GPS base station set up over certified survey control monuments. **Figure 2**, below, portrays the distribution of RTK point and basestation locations used for the current delivery of Columbia River survey areas. RTK points were collected on hard surfaces that were easily distinguishable within the LiDAR dataset. Paved surfaces, including roads, paths, and parking lots, were the primary surface target. After all paved surfaces had been exhausted, hard packed gravel roads became the secondary target for RTK, followed by hard packed dirt roads. Hard surfaces are targeted in areas that are clearly visible (and likely to remain visible) from the sky during data acquisition.

In order to facilitate comparisons with LiDAR data, RTK measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads. RTK points were taken no closer than one meter to any nearby terrain breaks such as road edges or drop offs to ensure an accurate comparison between RTK and LiDAR ground data. In addition, attempts were made to collect RTK points on locations that could be readily identified and occupied during subsequent field visits. RTK measurements were collected approximately 1-2 meters from one another to support measurement independence.

An RTK point acquisition period is five seconds long and includes three individual one-second measurements averaged together. The five second observation period ensures that an accurate RTK point was taken. RTK points were not taken during periods when PDOP was greater than three, when less than six satellites were visible, or when horizontal and vertical RMS values were greater than 0.03 m. An RMS value of 0.03 m indicates that an RTK measurement is within 0.03 m of its actual position 68% of the time. An RTK check point was also taken at the beginning and end of each RTK session as close to the base station location as possible to provide an on-the-spot vertical accuracy check.

Figure 2. RTK point and control monument locations used in Delivery 2, UTM 10.



3. LiDAR Data Processing

3.1 Applications and Work Flow Overview

1. Resolved kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data.

   Software: Waypoint GPS v.8.10, Trimble Geomatics Office v.1.62

2. Developed a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with attitude data Sensor head position and attitude were calculated throughout the survey. The SBET data were used extensively for laser point processing.

   Software: IPAS v.1.35

3. Calculated laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Created raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.2) format.

   Software: ALS Post Processing Software v.2.69

4. Imported raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter for pits/birds. Ground points were then classified for individual flight lines (to be used for relative accuracy testing and calibration).

   Software: TerraScan v.10.009

5. Using ground classified points per each flight line, the relative accuracy was tested. Automated line-to-line calibrations were then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calibrations were performed on ground classified points from paired flight lines. Every flight line was used for relative accuracy calibration.

   Software: TerraMatch v.10.006

6. Position and attitude data were imported. Resulting data were classified as ground and non-ground points. Statistical absolute accuracy was assessed via direct comparisons of ground classified points to ground RTK survey data. Data were then converted to orthometric elevations (NAVD88) by applying a Geoid03 correction. Ground models were created as a triangulated surface and exported as ArcInfo ASCII grids at a 1 –meter pixel resolution.

   Software: TerraScan v.10.009, ArcMap v. 9.3.1, TerraModeler v.10.004

3.2 Aircraft Kinematic GPS and IMU Data

LiDAR survey datasets were referenced to the 1 Hz static ground GPS data collected over pre-surveyed monuments with known coordinates. While surveying, the aircraft collected 2 Hz kinematic GPS data, and the onboard inertial measurement unit (IMU) collected 200 Hz aircraft attitude data. Waypoint GPS v.8.10 was used to process the kinematic corrections for the aircraft. The static and kinematic GPS data were then post-processed after the survey to obtain an accurate GPS solution and aircraft positions. IPAS v.1.35 was used to develop a trajectory file that includes corrected aircraft position and attitude information. The trajectory data for the entire flight survey session were incorporated into a final smoothed best estimated trajectory (SBET) file that contains accurate and continuous aircraft positions and attitudes.

3.3 Laser Point Processing

Laser point coordinates were computed using the IPAS and ALS Post Processor software suites based on independent data from the LiDAR system (pulse time, scan angle), and aircraft trajectory data (SBET). Laser point returns (first through fourth) were assigned an associated (x, y, z) coordinate along with unique intensity values (0-255). The data were output into large LAS v. 1.2 files; each point maintains the corresponding scan angle, return number (echo), intensity, and x, y, z (easting, northing, and elevation) information.

These initial laser point files were too large for subsequent processing. To facilitate laser point processing, bins (polygons) were created to divide the dataset into manageable sizes (< 500 MB). Flightlines and LiDAR data were then reviewed to ensure complete coverage of the survey area and positional accuracy of the laser points.

Laser point data were imported into processing bins in TerraScan, and manual calibration was performed to assess the system offsets for pitch, roll, heading and scale (mirror flex). Using a geometric relationship developed by Watershed Sciences, each of these offsets was resolved and corrected if necessary.

LiDAR points were then filtered for noise, pits (artificial low points) and birds (true birds as well as erroneously high points) by screening for absolute elevation limits, isolated points and height above ground. Each bin was then manually inspected for remaining pits and birds and spurious points were removed. In a bin containing approximately 7.5-9.0 million points, an average of 50-100 points are typically found to be artificially low or high. Common sources of non-terrestrial returns are clouds, birds, vapor, haze, decks, brush piles, etc.

Internal calibration was refined using TerraMatch. Points from overlapping lines were tested for internal consistency and final adjustments were made for system misalignments (i.e., pitch, roll, heading offsets and scale). Automated sensor attitude and scale corrections yielded 3-5 cm improvements in the relative accuracy. Once system misalignments were corrected, vertical GPS drift was then resolved and removed per flight line, yielding a slight improvement (<1 cm) in relative accuracy.

The TerraScan software suite is designed specifically for classifying near-ground points (Soininen, 2004). The processing sequence began by 'removing' all points that were not 'near' the earth based on geometric constraints used to evaluate multi-return points. The resulting bare earth (ground) model was visually inspected and additional ground point modeling was performed in site-specific areas to improve ground detail. This manual editing of ground often occurs in areas with known ground modeling deficiencies, such as: bedrock outcrops, cliffs, deeply incised stream banks, and dense vegetation. In some cases, automated ground point classification erroneously included known vegetation (i.e., understory, low/dense shrubs, etc.). These points were manually reclassified as non-grounds. Ground surface rasters were developed from triangulated irregular networks (TINs) of ground points.

4. LiDAR Accuracy Assessment

Our LiDAR quality assurance process uses the data from the real-time kinematic (RTK) ground survey conducted in the survey area. For both the UTM 10 and UTM 11 areas delivered to date, a total of **8789 RTK** GPS measurements were collected on hard surfaces distributed among multiple flight swaths. To assess absolute accuracy, we compared the location coordinates of these known RTK ground survey points to those calculated for the closest laser points.

4.1 Laser Noise and Relative Accuracy

Laser point absolute accuracy is largely a function of laser noise and relative accuracy. To minimize these contributions to absolute error, we first performed a number of noise filtering and calibration procedures prior to evaluating absolute accuracy.

Laser Noise

For any given target, laser noise is the breadth of the data cloud per laser return (i.e., last, first, etc.). Lower intensity surfaces (roads, rooftops, still/calm water) experience higher laser noise. The laser noise range for this survey was approximately 0.02 meters.

Relative Accuracy

Relative accuracy refers to the internal consistency of the data set - the ability to place a laser point in the same location over multiple flight lines, GPS conditions, and aircraft attitudes. Affected by system attitude offsets, scale, and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the LiDAR system is well calibrated, the line-to-line divergence is low (<10 cm). See Appendix A for further information on sources of error and operational measures that can be taken to improve relative accuracy.

Relative Accuracy Calibration Methodology

1. Manual System Calibration: Calibration procedures for each mission require solving geometric relationships that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.
2. Automated Attitude Calibration: All data were tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and

heading) and scale were solved for each individual mission and applied to respective mission datasets. The data from each mission were then blended when imported together to form the entire area of interest.

3. Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

4.2 Absolute Accuracy

The vertical accuracy of the LiDAR data is described as the mean and standard deviation (sigma ~ σ) of divergence of LiDAR point coordinates from RTK ground survey point coordinates. To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y, and z are normally distributed, thus we also consider the skew and kurtosis of distributions when evaluating error statistics.

Statements of statistical accuracy apply to fixed terrestrial surfaces only and may not be applied to areas of dense vegetation or steep terrain. To calibrate laser accuracy for the Delivery 2 LiDAR dataset, 3837 RTK points were collected on fixed, hard-packed road surfaces within the survey area.

5. Study Area Results

Summary statistics for point resolution and accuracy (relative and absolute) of the LiDAR data collected in the Columbia River survey areas are presented below in terms of central tendency, variation around the mean, and the spatial distribution of the data (for point resolution by quadrangle).

5.1 Data Summary

Table 3. *Resolution and Accuracy - Specifications and Achieved Values*

	Targeted	**Achieved**
Resolution:		
UTM 10	≥ 8 points/m^2	8.06 points/m^2
***Vertical Accuracy (1 σ):**		
UTM 10	<13 cm	4.1 cm

* Based on 4983 hard-surface control points within UTM 10

5.2 Data Density/Resolution

The average first-return density of the UTM 10 delivered dataset is 8.06 points per square meter (**Table 3**). The initial dataset, acquired to be 8 points per square meter, was filtered as described previously to remove spurious or inaccurate points. Additionally, some types of surfaces (i.e., dense vegetation, breaks in terrain, steep slopes, water) may return fewer pulses (delivered density) than the laser originally emitted (native density). Since this survey focused on a narrow corridor buffering the Columbia River, the reported first return density is artificially low.

Ground classifications were derived from automated ground surface modeling and manual, supervised classifications where it was determined that the automated model had failed. Ground return densities will be lower in areas of dense vegetation, water, or buildings.
The maps in **Figures 3 - 10** identify the average native and ground point densities for each USGS 0.75 minute quad. Tiles with greater than 20 million points were divided in half to keep LAS file sizes manageable.

Cumulative LiDAR data resolution for UTM 10 of the Columbia River survey:

- Average Point (First Return) Density = 8.06 points/m^2
- Average Ground Point Density = 1.22 points/m^2

Figure 3. *Density distribution for first return laser points in UTM 10.*

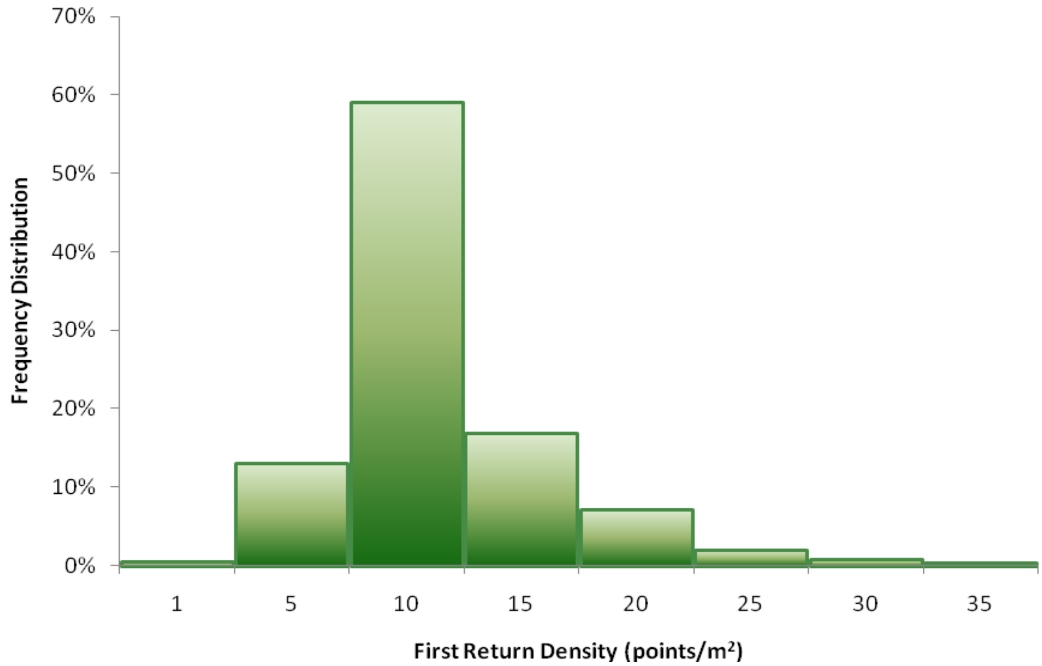


Figure 4. *Density distribution for ground-classified laser points in, UTM 10.*

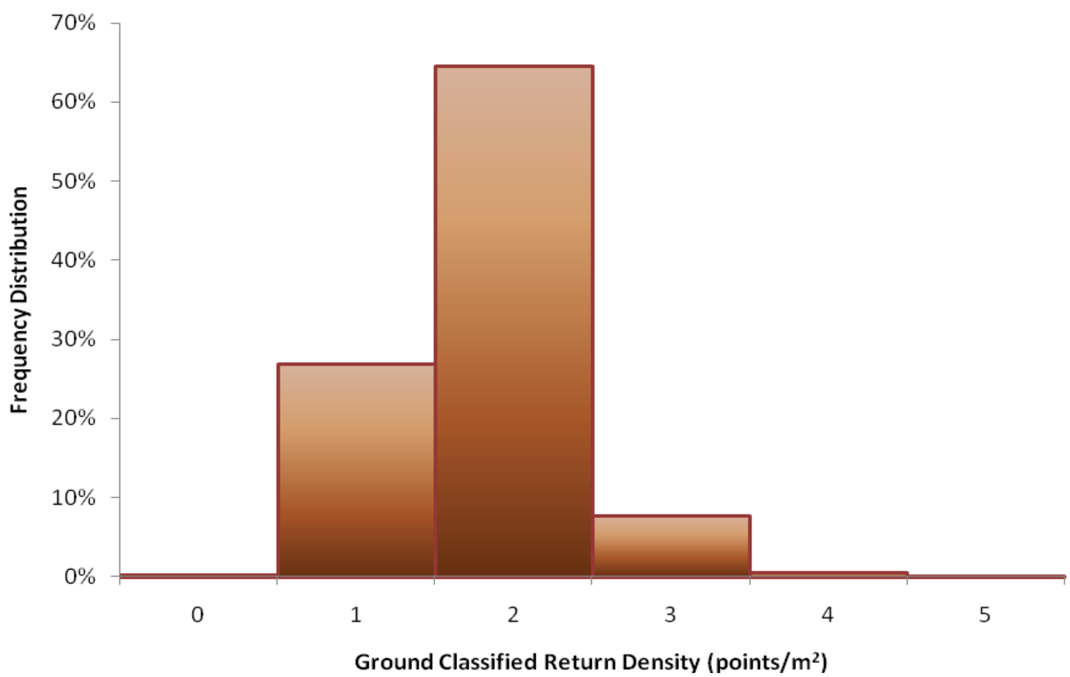


Figure 5*. Delivery 1, UTM 10 density distribution map for ground return points by USGS 0.75 minute quads.*

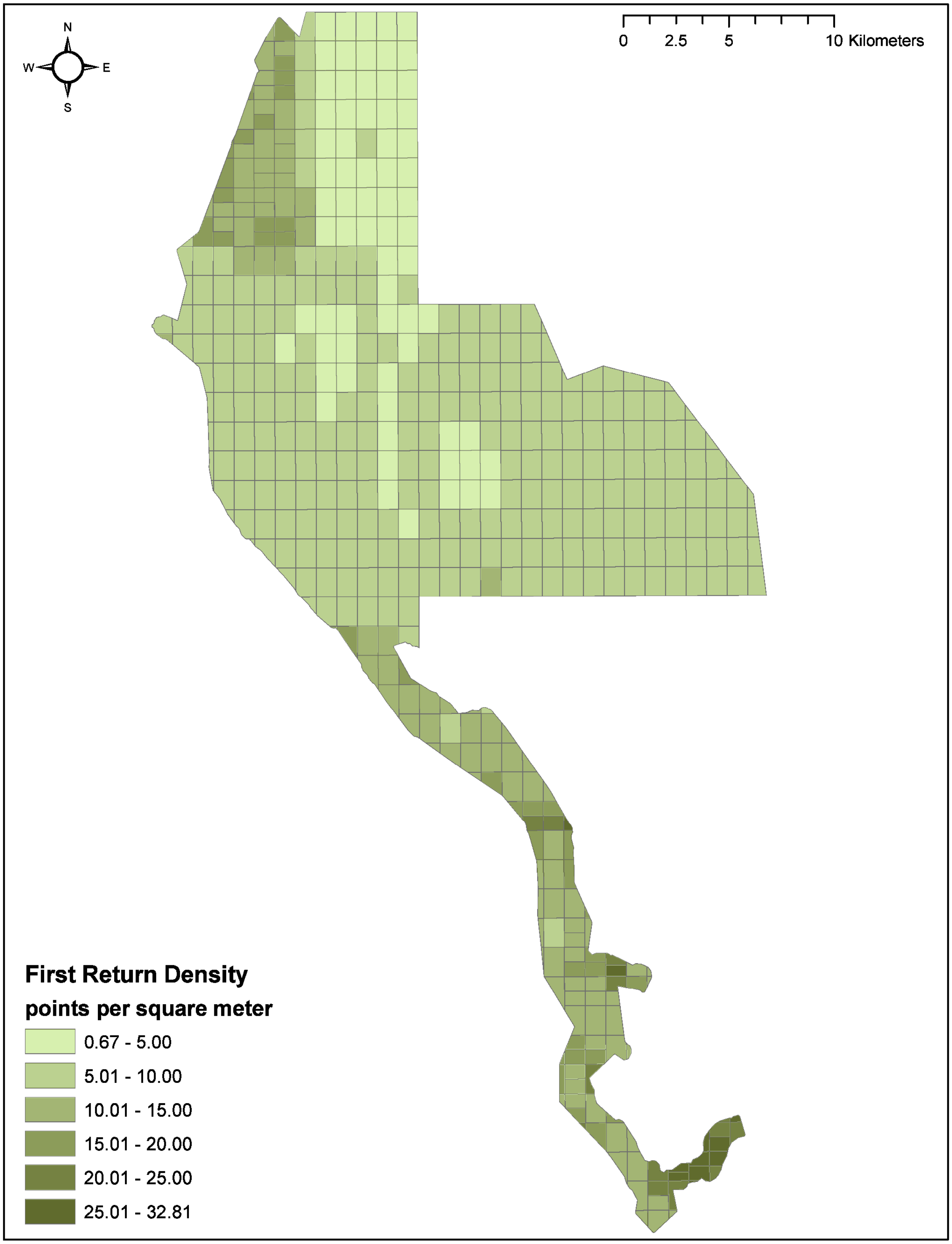


Figure 6. *Delivery 1, UTM 10 density distribution map for ground return points by USGS 0.75 minute quads.*

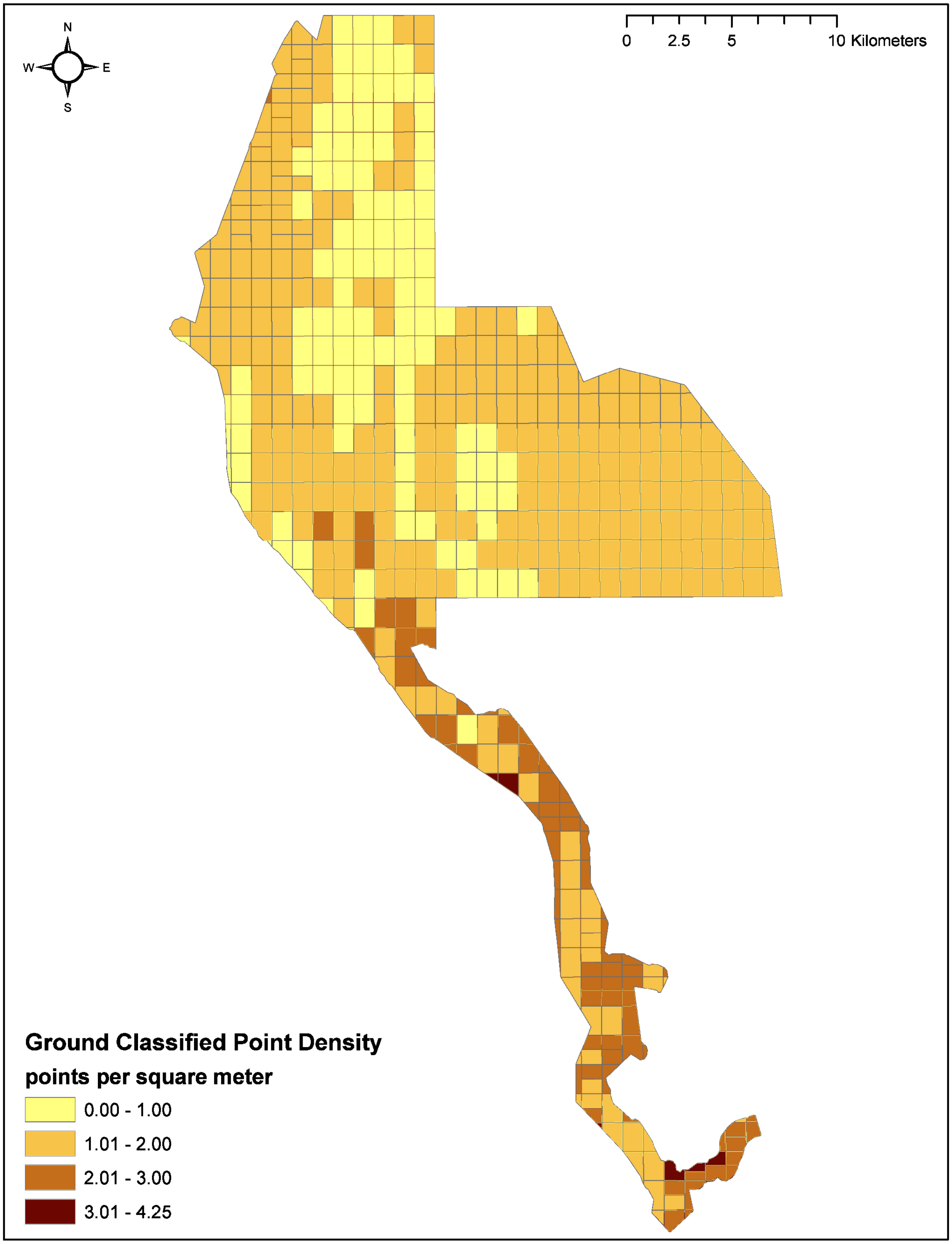


***Figure 7**. Delivery 1, UTM 11 density distribution map for first return points by USGS 0.75 minute quads.*

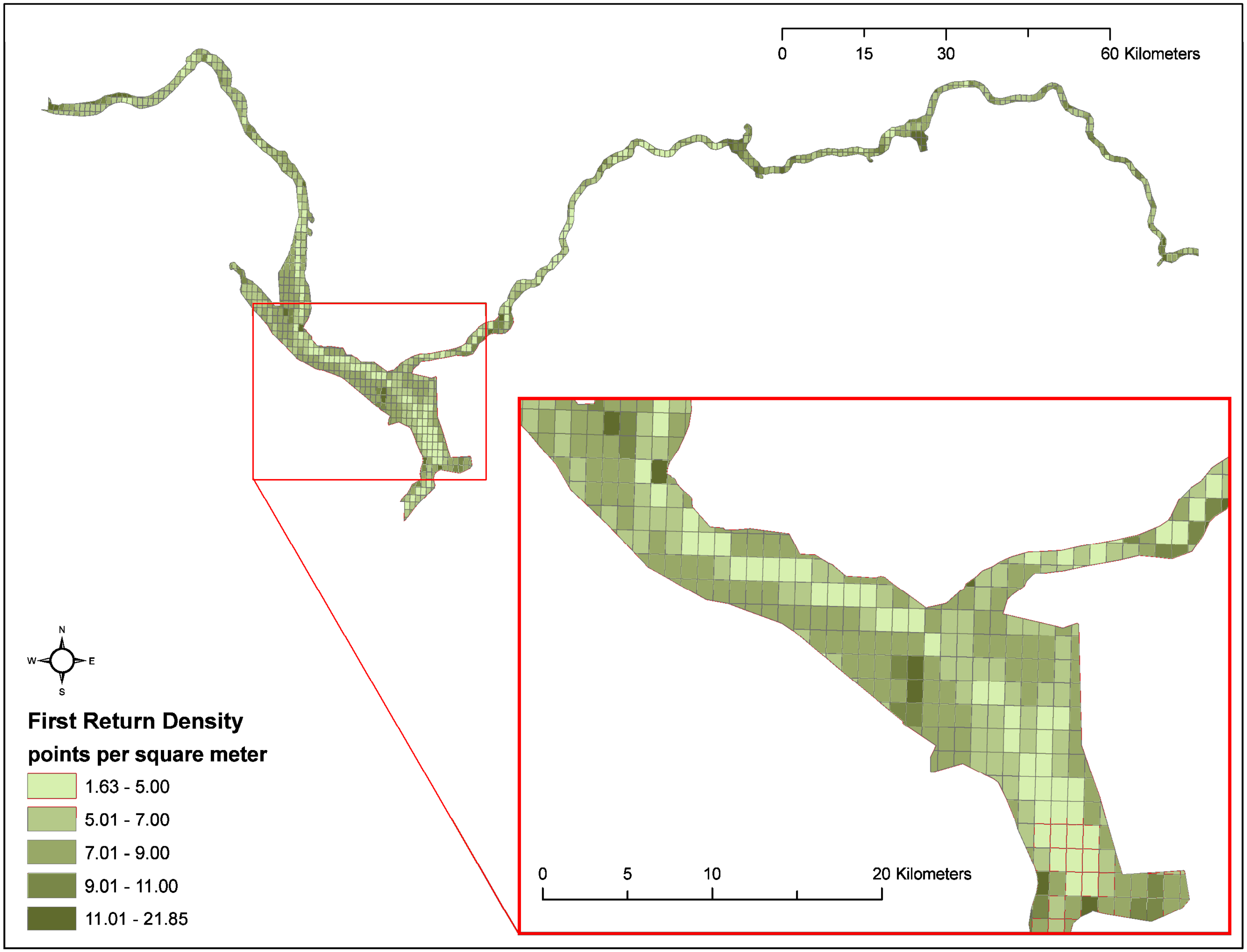


***Figure 8**. Delivery 1, UTM 11 density distribution map for ground return points by USGS 0.75 minute quads.*

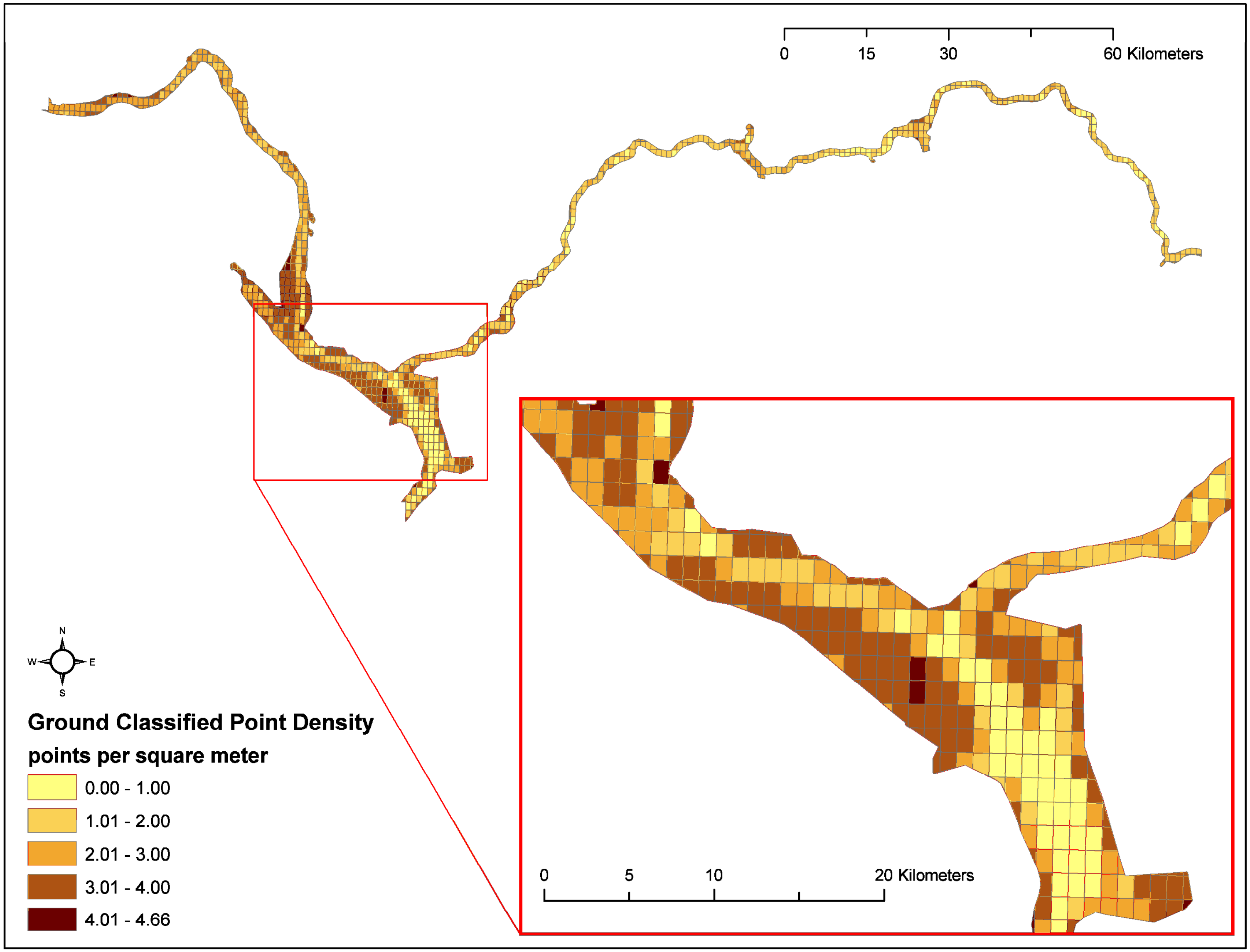


Figure 9. *Delivery 2, UTM 10 density distribution map for ground return points by USGS 0.75 minute quads.*

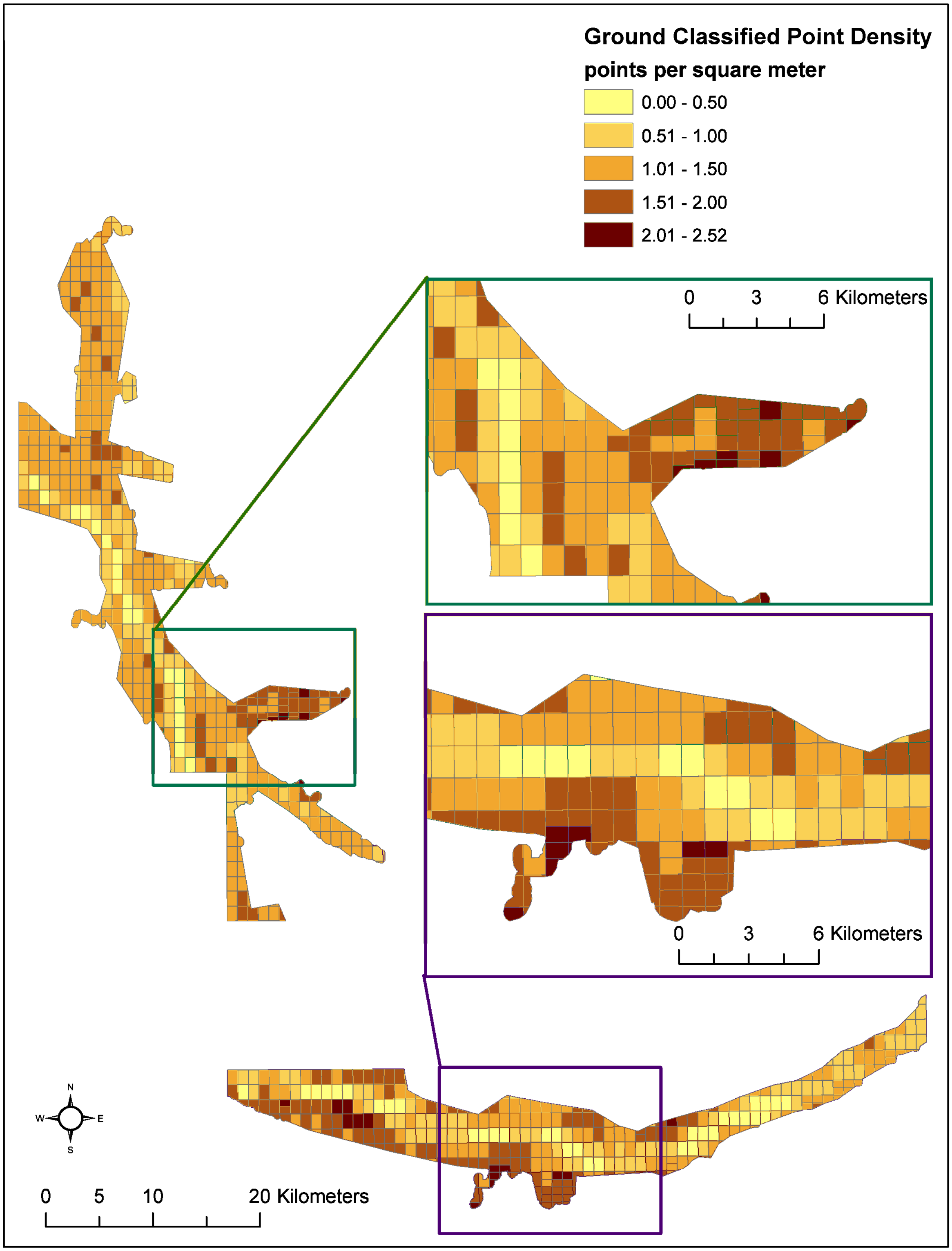
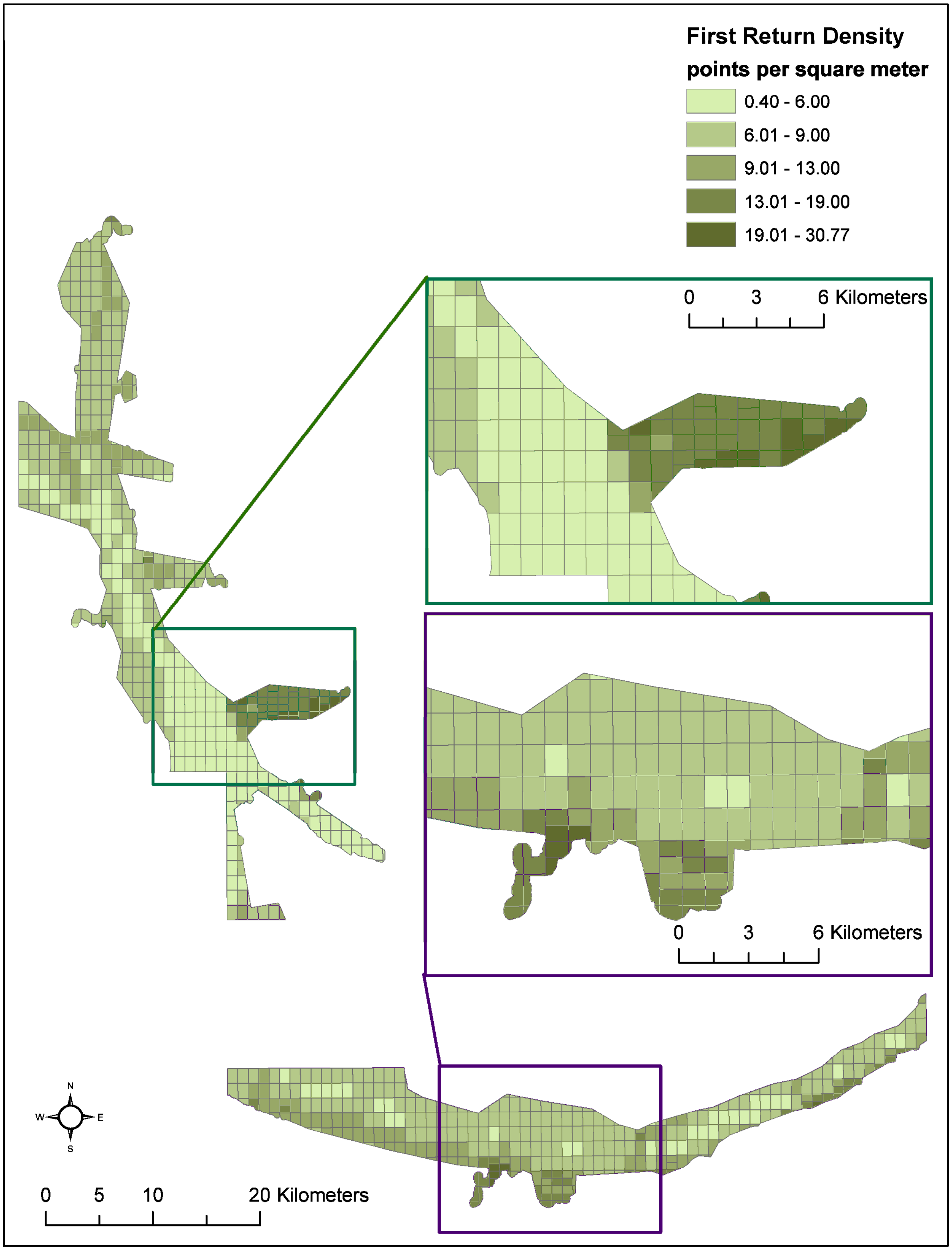


Figure 10. *Delivery 2, UTM 10 density distribution map for first return points by USGS 0.75 minute quads.*



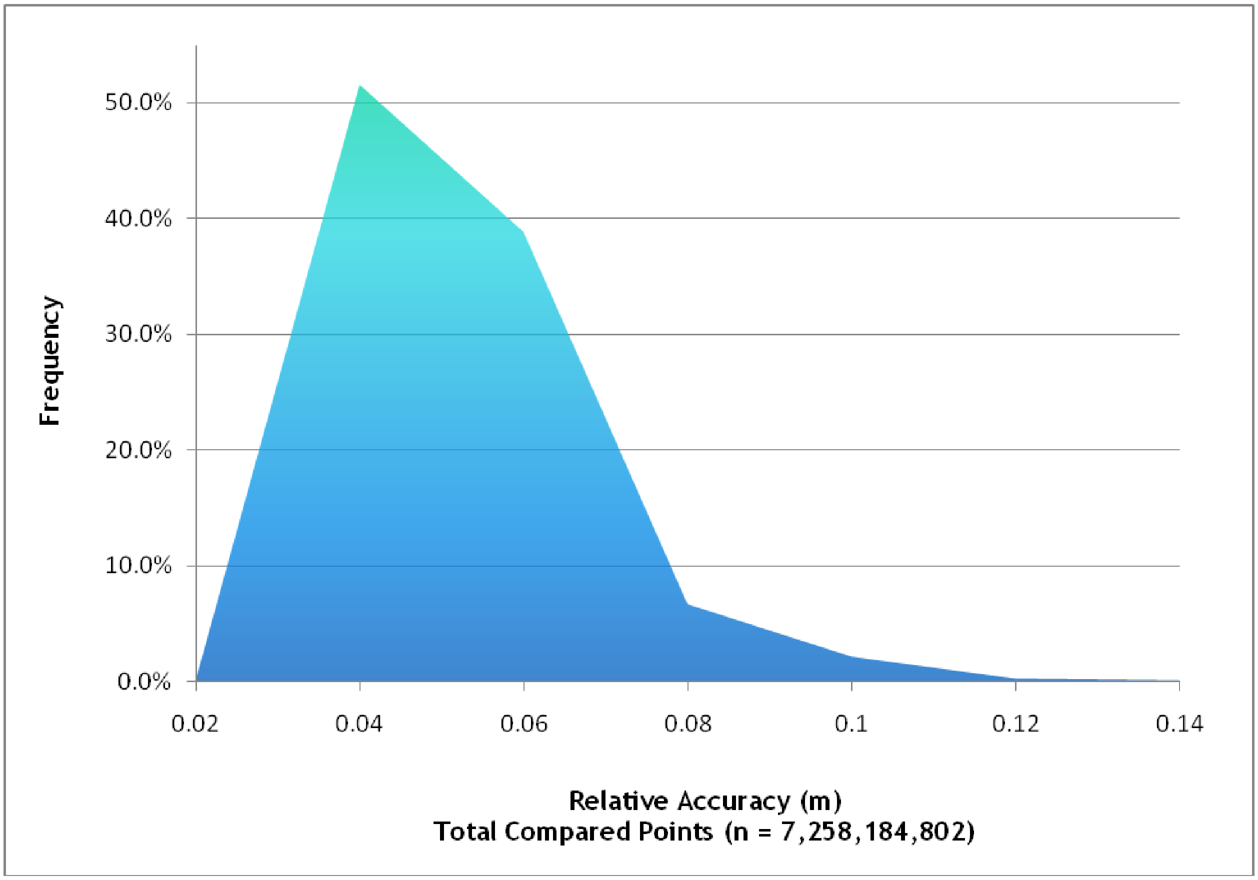
5.3 Relative Accuracy Calibration Results

Relative accuracies for the Columbia River survey area measure the full survey calibration including areas outside the delivered boundary.

Relative accuracy statistics for UTM 10 delivered to date

- Project Average = 0.039m
- Median Relative Accuracy = 0.040m
- 1σ Relative Accuracy = 0.044m
- 2σ Relative Accuracy = 0.072m

***Figure 11**. Distribution of relative accuracies per flight line, non slope-adjusted for UTM 10*



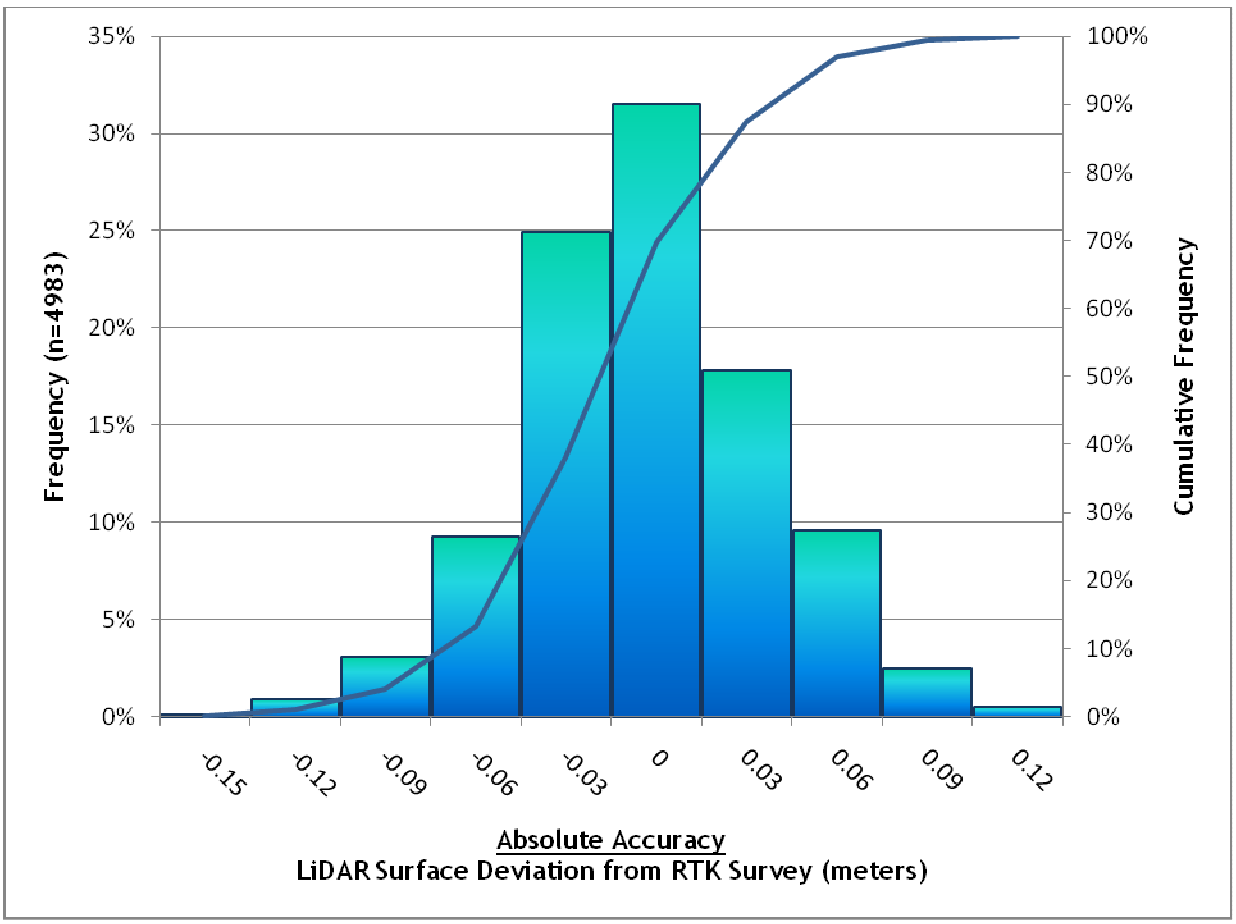
5.4 Absolute Accuracy

Absolute accuracies for the Columbia River survey areas:

Table 4. *Absolute Accuracy for UTM 10 – Deviation between laser points and RTK hard surface survey points*

RTK Survey Sample Size (n): 4983	
Root Mean Square Error (RMSE) = (0.044m)	Minimum Δz = -0.204m
Standard Deviations 1 sigma (σ): (0.041m) 2 sigma (σ): (0.087m)	Maximum Δz = 0.119m Average Δz = -0.018m

Figure 12. *Absolute Accuracy - Histogram Statistics, based on 4983 RTK points in UTM 10*



6. Breakline Enforced Terrain Model

David C. Smith and Associates (DSA) created breaklines for the Columbia River study area using LiDAR-grammetry techniques. **Table 5** describes the type and definition of each breakline collected. The breaklines were used to supplement the LiDAR data in creation of a final ground model. Water boundaries were enforced using hard breaklines and water surfaces were flattened based on the elevation from the breaklines. The breakline boundaries were also used to class any points with ground or model key point classification within the water delineated areas.

***Table 5**. Breaklines collected for the Columbia River study area, see Appendix B for feature definitions.*

Feature	Implementation
Breakline	Hard Breakline
Breakline Obscured	Hard Breakline
Water Main	Hard Breakline
Water Island	Hard Breakline
Water Other	Hard Breakline
Buildings	Provided as Feature

7. Projection/Datum and Units

	Projection:	UTM Zone 10 and 11, NAD 83
Datum	**Vertical:**	NAVD88 Geoid09
	Horizontal:	NAD83
	Units:	meters

8. Deliverables

Point Data:	• All Returns (LAS 1.2 format)
Vector Data:	• Tile Index of LiDAR points (USGS 0.75 minute quads, shapefile) • Tile Index of DEM rasters (USGS 7.5 minute quads, shapefile) • 1-hz SBET files (shapefile) • Breaklines (dxf format) *provided by DSA* • Watermask (dxf.format) *provided by DSA*

Raster Data:	• Elevation models (1 m resolution)
	  • Breakline Enforced Bare Earth Model (ESRI GRID format)
	  • Highest Hit Model (ESRI GRID format)
	• Intensity images (GeoTIFF format, 1 m resolution)

Data Report:	Full report containing introduction, methodology, and accuracy

9. Selected Images

Figure 13. *3D view looking North up the Columbia River with views of Locke Island near Hanford Reach. Top image derived from ground-classified LiDAR points, bottom image derived from highest-hit LiDAR points colored by NAIP imagery.*

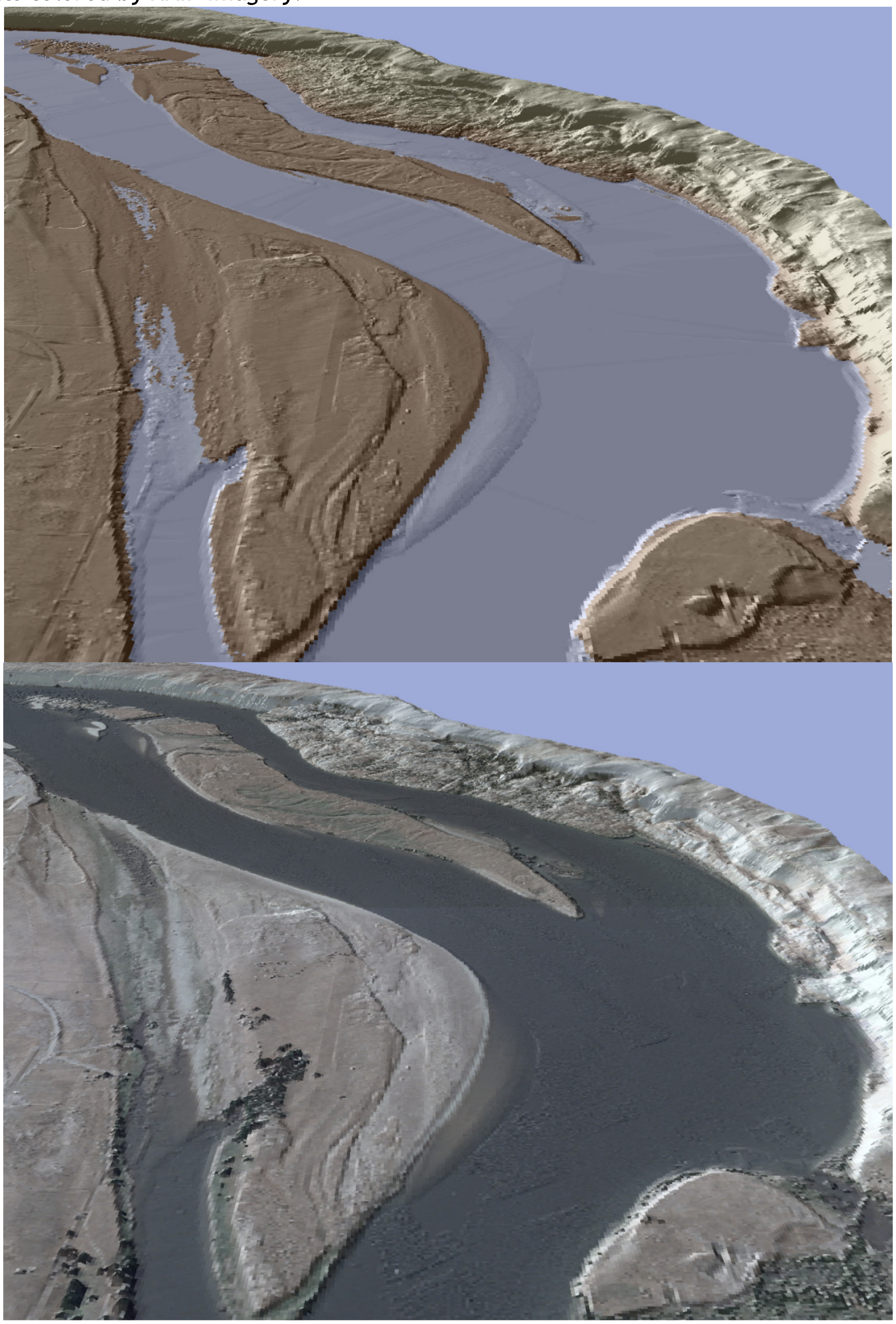


Figure 14. *3D view looking North west over Richland, WA with views of Bateman Island and Riverview and Chamna Nature Preserves . Top image derived from ground-classified LiDAR points, bottom image derived from highest-hit LiDAR points.*

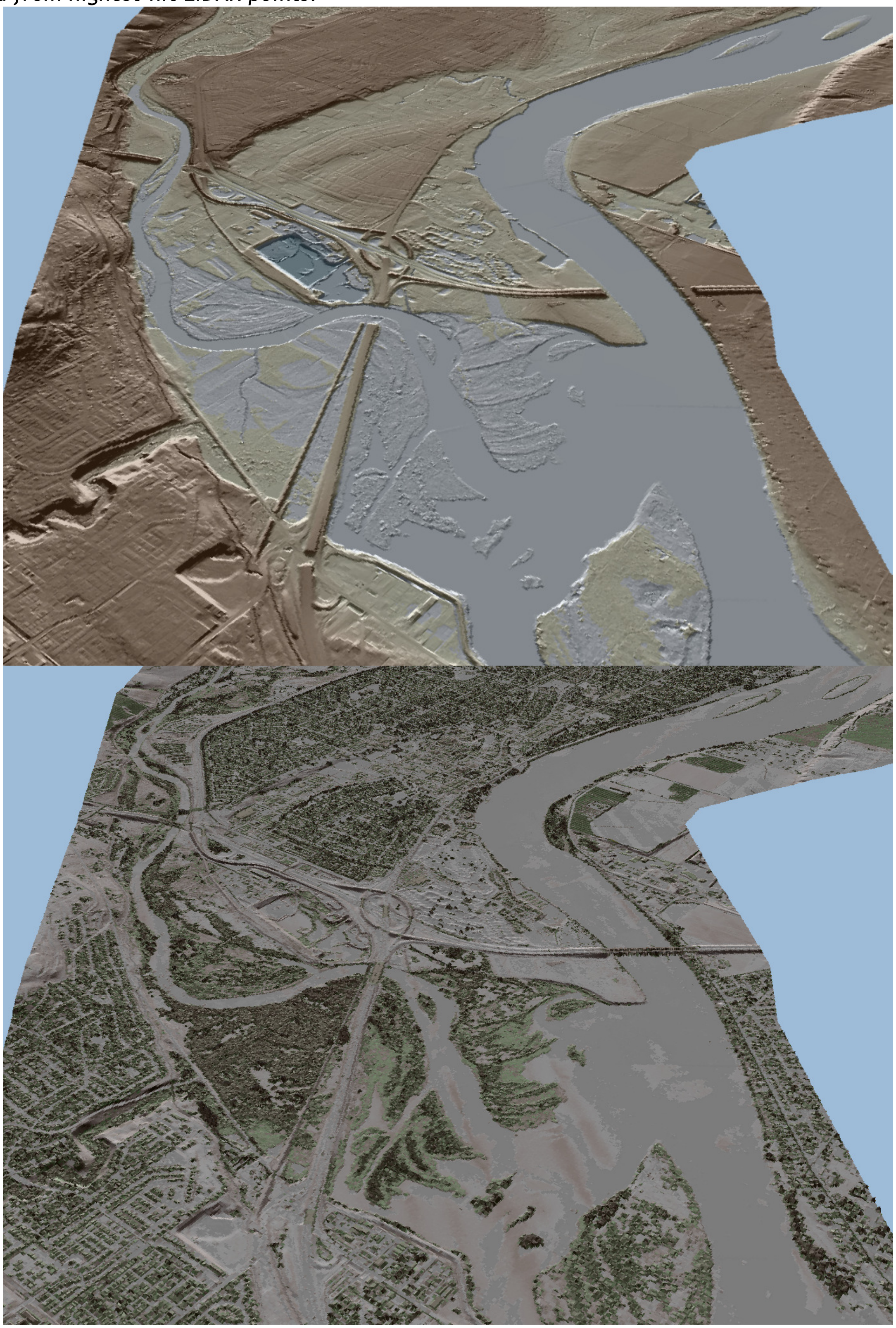


Figure 15. *3d point cloud looking north at I-5 crossing the Columbia River. MLK Blvd can be seen over I-5 and Portland Harbor is in the distance.*

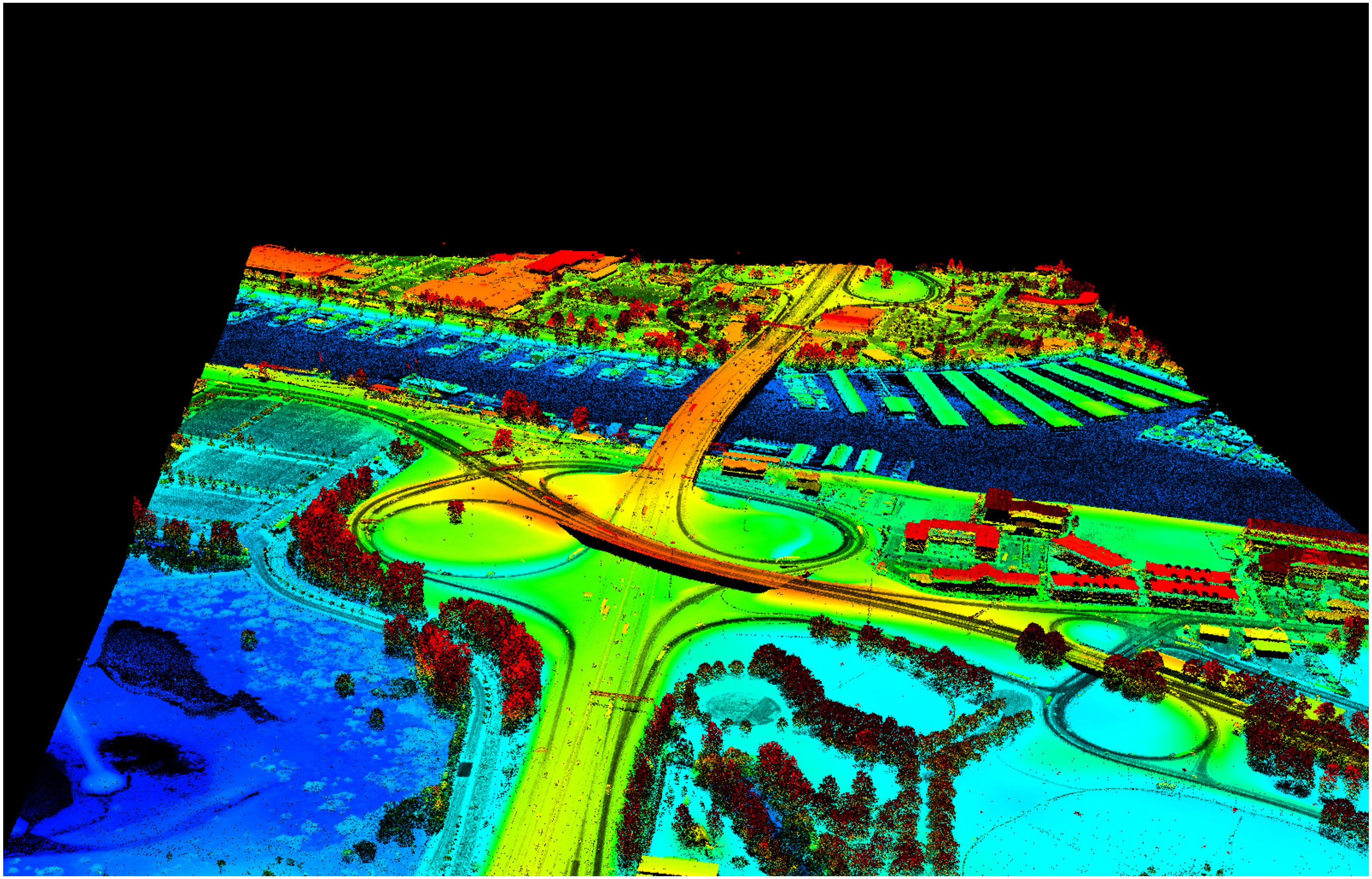


Figure 16. *3d point cloud looking southeast at middle section of Hayden island. A railroad bridge can be seen crossing the Columbia River with Portland Harbor in the far distant corner.*

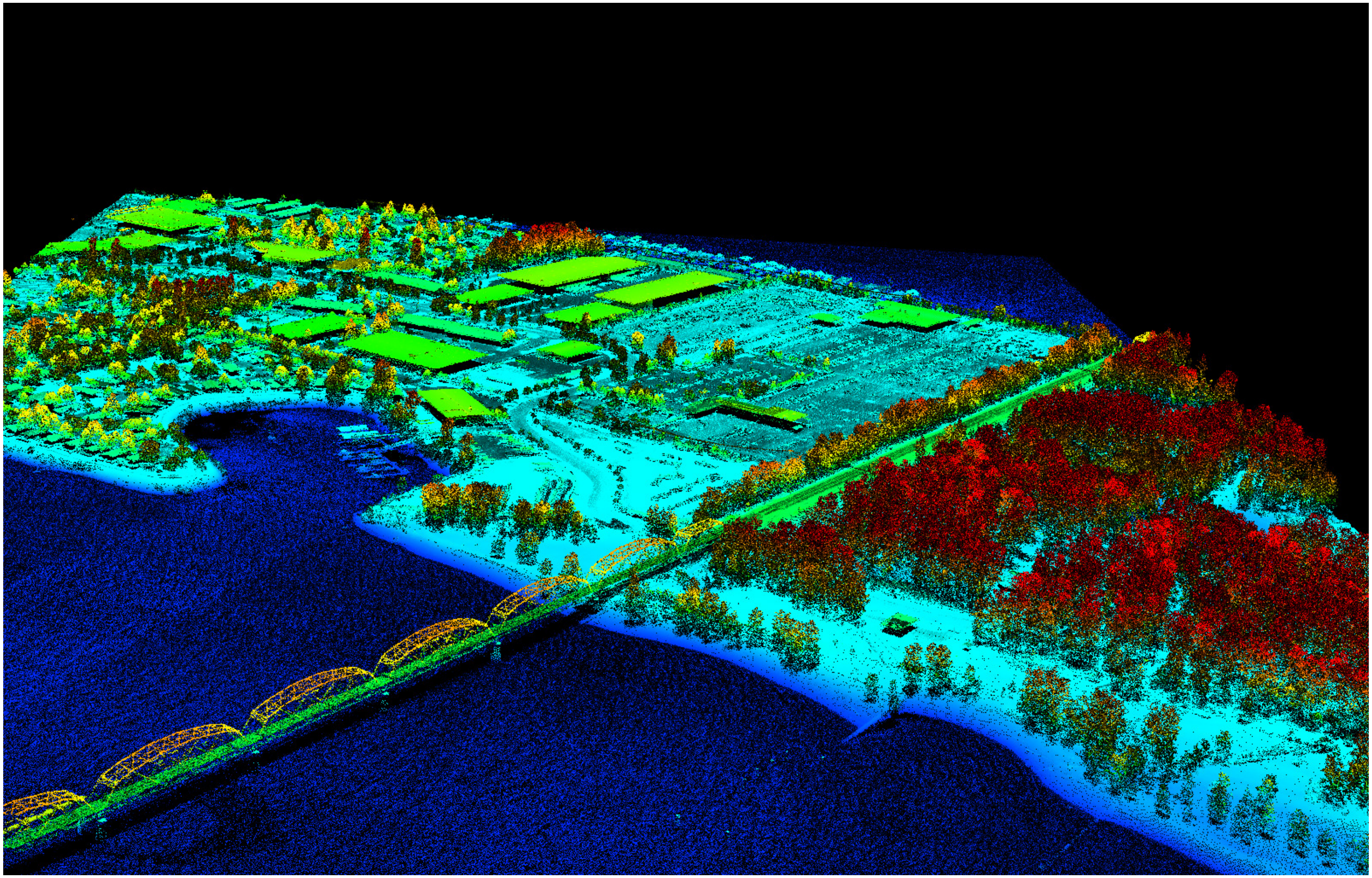
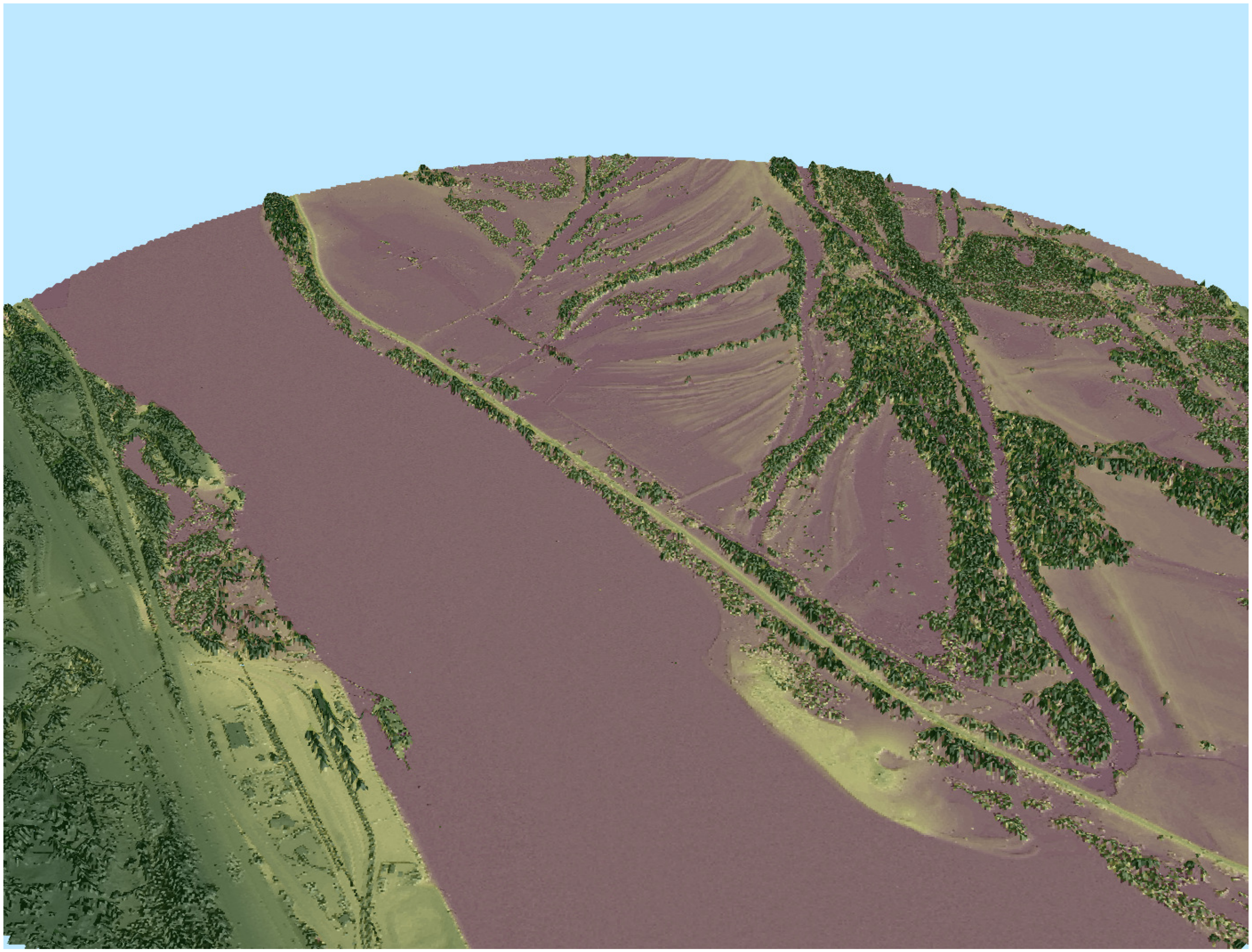


Figure 17. *Highest hit model looking South along the Columbia River. Drainage patterns on the right hand side highlight Cottonwood Lake and Swan Lake. Daves Slough is on the far right hand side of image. Looking at Deer Island from Washington border.*



10. Glossary

1-sigma (σ) Absolute Deviation: Value for which the data are within one standard deviation (approximately 68th percentile) of a normally distributed data set.

2-sigma (σ) Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set.

Root Mean Square Error (RMSE): A statistic used to approximate the difference between real-world points and the LiDAR points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

Pulse Rate (PR): The rate at which laser pulses are emitted from the sensor; typically measured as thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the Leica ALS 50 Phase II system can record *up to four* wave forms reflected back to the sensor. Portions of the wave form that return earliest are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

Accuracy: The statistical comparison between known (surveyed) points and laser points. Typically measured as the standard deviation (sigma, σ) and root mean square error (RMSE).

Intensity Values: The peak power ratio of the laser return to the emitted laser. It is a function of surface reflectivity.

Data Density: A common measure of LiDAR resolution, measured as points per square meter.

Spot Spacing: Also a measure of LiDAR resolution, measured as the average distance between laser points.

Nadir: A single point or locus of points on the surface of the earth directly below a sensor as it progresses along its flight line.

Scan Angle: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase.

Overlap: The area shared between flight lines, typically measured in percents; 100% overlap is essential to ensure complete coverage and reduce laser shadows.

DTM / DEM: These often-interchanged terms refer to models made from laser points. The digital elevation model (DEM) refers to all surfaces, including bare ground and vegetation, while the digital terrain model (DTM) refers only to those points classified as ground.

Real-Time Kinematic (RTK) Survey: GPS surveying is conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

11. Citations

Soininen, A. 2004. TerraScan User's Guide. TerraSolid.

Appendix A

LiDAR accuracy error sources and solutions:

Type of Error	Source	Post Processing Solution
GPS (Static/Kinematic)	Long Base Lines	None
	Poor Satellite Constellation	None
	Poor Antenna Visibility	Reduce Visibility Mask
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings
	Inaccurate System	None
Laser Noise	Poor Laser Timing	None
	Poor Laser Reception	None
	Poor Laser Power	None
	Irregular Laser Shape	None

Operational measures taken to improve relative accuracy:

1. Low Flight Altitude: Terrain following is employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (i.e., ~ 1/3000th AGL flight altitude).
2. Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return is a function of laser emission power, laser footprint, flight altitude and the reflectivity of the target. While surface reflectivity cannot be controlled, laser power can be increased and low flight altitudes can be maintained.
3. Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of $\pm 15^{o}$ from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.
4. Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). Before each flight, the PDOP was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1–second epochs was utilized and a maximum baseline length between the aircraft and the control points was less than 19 km (11.5 miles) at all times.
5. Ground Survey: Ground survey point accuracy (i.e. <1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey RTK points are distributed to the extent possible throughout multiple flight lines and across the survey area.
6. 50% Side-Lap (100% Overlap): Overlapping areas are optimized for relative accuracy testing. Laser shadowing is minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the most nadir portion of one flight line coincides with the edge (least nadir) portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.
7. Opposing Flight Lines: All overlapping flight lines are opposing. Pitch, roll and heading errors are amplified by a factor of two relative to the adjacent flight line(s), making misalignments easier to detect and resolve.

Appendix B

Breakline definitions as determined by DSA:

FEATURE:

BREAKLINE - Added to the ground model where the LiDAR ground points were missing or not properly defining the surface. Usually occured on sharp breaks associated with cliffs. These breaks are derived from the 1st return data and fit to the ground data.

BREAKLINE_OBSCURE - Added in vegetated areas where the LiDAR ground model was not complete due to dense vegetation. These lines are interpreted from visible data and fit to visible ground data.

WATER_MAIN - Main rivers, not including side rivers and streams. Designed to be the river in the center of the coverage area, Columbia, Snake, etc.

WATER_OTHER - Covers side rivers, lakes, ponds etc. This coverage is not intended to capture all water outside the main rivers but only water edges that need a breakline and need LiDAR data re-classified. No single line streams are collected.

WATER_ISLAND - Islands in the rivers and streams.

BUILDING - Visible and obvious buildings.

BUILDING_UNSURE - Features that appear to be buildings but might not be.

BUILDING_AREA - Large areas with a dense population of buildings, subdivisions, etc.